

The Impact of Cosmic Dust on Supernova Cosmology

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ABSTRACT

Extinction by intergalactic gray dust introduces a magnitude redshift dependent offset in the standard-candle relation of SN Ia. This leads to overestimated luminosity distances compared to a dust-free universe. Quantifying the amplitude of this systematic effect is crucial for an accurate determination of the dark energy parameters. In this paper we model the gray dust extinction in terms of the star-formation history of the Universe and the physical properties of the dust grains. We focus on a class of cosmic dust models which satisfy current observational constraints. These can produce an extinction as large as 0.08 mag at $z = 1.7$ and potentially disrupt the dark energy parameter inference from future SN surveys. In particular depending on the dust model we find that an unaccounted extinction can bias the estimation of a constant dark energy equation of state w by shifting its best fit value up to 20% from its true value. Near-IR broadband photometry will hardly detect this effect, while the induced decrement of the Balmer lines requires high signal-to-noise spectra. Indeed IR-spectroscopy will be needed for high redshift SNe. Cosmic dust extinction may also cause a detectable violation of the distance-duality relation. A more comprehensive knowledge of the physics of the IGM is necessary for an accurate modeling of intergalactic dust. Due to the large magnitude dispersion current luminosity distance measurements are insensitive to such possible extinction effects. In contrast these must be taken into account if we hope to disclose the true nature of dark energy with the upcoming generation of SN Ia surveys.

Key words: cosmology: theory - dust, extinction - supernova Ia - dark energy

1 INTRODUCTION

Dust particles are present in the interstellar medium causing the absorption of nearly 30 – 50% of light emitted by stars in the Galaxy. On the other hand very little is known about dust particles which may exist outside our galactic environment. Metal lines are observed in the X-ray spectra of galaxy clusters (e.g. Buote 2002) and in high redshift Lyman- α clouds (Cowie et al. 1995; Telfer et al. 2002). Infrared emissions of distant quasars have been attributed to the presence of large amounts of dust (Bertoldi et al. 2003; Robson et al. 2004). Therefore it has been speculated that some type of dust may be present in the low density intergalactic medium (IGM). Since conditions in the IGM are unfavorable to the formation of dust grains, if such a component exists it originates in stars. However it is unlikely that its properties are similar to those of interstellar grains. In fact because of the physical processes which expel dust from formation sites, intergalactic dust particles may undergo very different selection effects (Shustov & Vibe 1995; Davies et al. 1998; Aguirre 1999).

Since the early search for distant Supernovae Type Ia (SNe Ia) (Riess et al. 1998; Perlmutter et al. 1999), cosmic dust extinction was proposed to account for the observed dimming of supernova

luminosities at high redshift (Aguirre 1999). From several other observations we have now compelling evidence of the cosmological nature of this signal (De Bernardis et al. 2000; Percival et al. 2001; Spergel et al. 2003; Scranton et al. 2003; Tegmark et al. 2004). There is a general consensus that it is caused by a recent accelerated phase of expansion driven by a dark energy component. This can be the manifestation of a cosmological constant, or an exotic species of matter, or a different regime of gravity on the large scales. Distinguishing between these different scenarios has motivated a rich field of investigation.

Over the next decade numerous experiments will test dark energy using a variety of techniques. Surveys of SN Ia such as the proposed *SNAP*, *JEDI* or *ALPACA* will play a leading role by providing very accurate luminosity distance measurements. The success of this program will mostly depend on the ability to identify and reduce possible sources of systematic uncertainties affecting the SN Ia standard-candle relation.

Here we address the impact of cosmic “gray” dust. Our aim is to study this particular systematic effect from an astrophysical point of view. Differently from the original proposal by Aguirre (1999), we do not look for dust models which mimic the dimming of an accelerating universe. Instead we estimate how an hypothetical cosmic gray dust model which satisfies existing astrophysical constraints may affect the dark energy parameter estimation from

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future SN observations. In order to do so we evaluate the dust extinction from first principles by modeling the IGM dust in terms of the star-formation history (SFH) of the Universe and the physical properties of the dust grains. This will allow us to establish how the uncertainties in the cosmic dust model, which depends on the complex physics of the IGM, relate to expected cosmological parameter errors.

The paper is organized as follows: in Section 2 we discuss the existing constraints on cosmic gray dust and evaluate the expected extinction for different IGM dust models. We evaluate the impact on the dark energy parameter inference and describe the results of our analysis in Section 3. In Section 4 we compute the signature of dust models in near-infrared photometric measurements and the decrement of the Balmer lines. In Section 5 we discuss the violation of the distance-duality relation. Finally in Section 6 we present our conclusions.

2 COSMIC GRAY DUST

2.1 Observational Constraints

Typical dust extinction is correlated with reddening of incoming light, therefore it can be revealed by simple color analysis. Using this technique the interstellar extinction law has been estimated over a wide range of wavelengths (e.g. Cardelli et al. 1989). However this method is not effective for absorption caused by “gray” dust. As suggested by Aguirre (1999), astrophysical processes which transfer dust into the IGM can preferentially destroy small grains over the large ones. Those surviving have radii $a \gtrsim 0.01 \mu\text{m}$. In such a case intergalactic dust may consist of particles which induce very little reddening (hence gray), while still able to cause large extinction effects.

The possibility of gray dust being entirely responsible for the dimming of high redshift SN Ia has been now ruled out. For instance Aguirre & Haiman (2000) showed that the density of dust necessary to reconcile SN data with a flat matter dominated universe is incompatible with the limits inferred from the far-infrared background (FIRB) as measured by the DIRBE/FIRAS experiment. Recently Bassett & Kunz (2004b) have excluded this scenario at more than 4σ by testing the distance-duality relation. Nevertheless the actual amount of dust in the IGM and its composition remain unknown.

Constraints on cosmic dust extinction have been inferred from color analysis of distant quasars (Mortzell & Goobar 2003; Ostman & Mortzell 2005). Assuming the interstellar extinction law (Cardelli et al. 1989; Fitzpatrick 1999), these studies have confirmed that dust dimming cannot be larger than 0.2 mag at $z = 1$ and also indicated that if any gray dust component is present in the IGM it cannot induce extinction larger than 0.1 mag. For an early study of the effect of intergalactic extinction on cosmological expansion measurements see also Meinel (1981).

Indeed infrared (IR) observations may turn out to be more informative. As an example Aguirre & Haiman (2000) have suggested that resolving the Far Infrared Background (FIRB) will provide a definitive test of the IGM dust. Some quantitative limits have also been derived from the thermal history of the IGM (Inoue & Kamaya 2003).

A more direct constraint on the density of cosmic dust particles has been obtained by Paerels et al. (2002) from the analysis of X-ray scattering halo around a distant quasar at $z = 4.30$. In particular for grains of size $\sim 1 \mu\text{m}$ the total cosmic dust density is

$\Omega_{\text{dust}}^{\text{IGM}} \lesssim 10^{-6}$, while for $0.1 \mu\text{m}$ grains the constraint is one order of magnitude weaker. Compatible limits were also found by Inoue & Kamaya (2004) using existing bounds on SN Ia extinction and reddening.

As we will see in the next section a better knowledge of these quantities is necessary if we hope to measure the dark energy parameters with high accuracy.

2.2 Intergalactic Dust Extinction

In order to estimate the extinction from intergalactic gray dust we need to determine the evolution of dust density in the IGM. Since dust particles are made of metals, the first step is to evaluate the evolution of the cosmic mean metallicity from the star formation history of the Universe (Aguirre & Haiman 2000). For simplicity we can assume that metals are instantaneously ejected from newly formed stars. In such a case the metal ejection rate per unit comoving volume at redshift z can be written as (Tinsley 1980):

$$\dot{\rho}_Z(z) = \dot{\rho}_{\text{SFR}}(z)y_Z, \quad (1)$$

where $\dot{\rho}_{\text{SFR}}$ is the star formation rate and y_Z is the mean stellar yield, namely the average mass fraction of a star that is converted to metals. The value of y_Z is slightly sensitive to the initial mass function (IMF) and may also change with redshift if the IMF varies with time. For simplicity we assume y_Z to be constant.

From Eq. (1) it follows that the mean cosmic metallicity is given by (Inoue & Kamaya 2004):

$$Z(z) = \frac{y_Z}{\Omega_b \rho_c} \int_z^{z_S} \dot{\rho}_{\text{SFR}}(z') \frac{dz'}{H(z')(1+z')}, \quad (2)$$

where Ω_b is the baryon density, ρ_c is the current critical density, $H(z)$ is the Hubble rate and z_S redshift at which star formation began. There is little dependence on z_S for $z \lesssim 3$, provided that the star formation begin at $z_S \gtrsim 5$. Without loss of generality we set its value to $z_S = 10$.

Following the notation of Inoue & Kamaya (2004), we introduce a further parameter which describes the mass fraction of dust to the total metal mass, $\chi = \mathcal{D}/Z$, where \mathcal{D} is the dust-to-gas ratio of the IGM. The latter depends on the mechanism which expel dust from galaxies and in principle may evolve with redshift according to the dominant process responsible for the transfer (e.g. stellar winds, SN II explosions, radiation pressure). Only recently authors have began to study the metal enrichment of the IGM using numerical simulations (see for instance Bianchi & Ferrara 2006). As we lack of any guidance we simply assume that the dust-to-gas ratio scales with the mean metallicity and consider χ as a constant free parameter.

Another open issue concerns the spatial distribution of dust particles in the IGM. It has been argued that a clumped gray dust would cause a dispersion of supernova magnitudes larger than the observed one. Consequently if a gray dust component exists it must be nearly homogeneously distributed. However this does not necessarily implies a strong constraint on the gray dust hypothesis. In fact the overall dispersion at a given redshift goes roughly as $\Delta \propto 1/\sqrt{N}$ where N is the number of homogeneous dust patches along the line-of-sight (Aguirre 1999). Numerical simulations indicate that dust grains can diffuse in one billion years over scales of few hundreds Kpc (Aguirre et al. 2001). This corresponds to $N \gg 1$ for high redshift SNe, in which case the dispersion would be small. Indeed more detailed studies are needed, here we limit our analysis to a homogeneous dust distribution.

The differential number density of dust particles in a unit physical volume reads as

$$\frac{dn_d}{da}(z) = \frac{\chi Z(z) \Omega_b \rho_c (1+z)^3}{4\pi a^3 \varrho/3} N(a), \quad (3)$$

where ϱ is the grain material density and $N(a)$ is the grain size distribution normalized to unity.

The amount of cosmic dust extinction on a source at redshift z observed at the rest-frame wavelength λ integrated over the grain size distribution is then given by:

$$\frac{A_\lambda(z)}{\text{mag}} = 1.086\pi \int_0^z \frac{c dz'}{(1+z')H(z')} \int a^2 Q_m^\lambda(a, z') \frac{dn_d}{da}(z') da, \quad (4)$$

where $Q_m^\lambda(a, z')$ is the extinction efficiency factor which depends on the grain size a and complex refractive index m , and c is the speed of light. Hence the extinction at a given redshift depends on the dust properties and the metal content of the IGM. More specifically for a given cosmological background, a model of dust is specified by the grain composition, size distribution and material density, the mean interstellar yield, the star formation history and the IGM dust-to-total-metal mass ratio.

None of these parameters is precisely known, leaving us with a potentially large uncertainty about the level of cosmic dust extinction.

In the following we assume a standard flat LCDM model with Hubble constant $H_0 = 70 \text{ Km s}^{-1} \text{ Mpc}^{-1}$, matter density $\Omega_m = 0.30$ and baryon density $\Omega_b = 0.04$.

Several studies have suggested that the size of IGM dust grains varies in the range $0.05 - 0.2 \mu\text{m}$ (Ferrara et al. 1991; Shustov & Vibe 1995; Davies et al. 1998). Smaller grains ($a \lesssim 0.05 \mu\text{m}$) are either destroyed by sputtering or unable to travel far from formation sites as they are inefficiently pushed away by radiation pressure; in contrast grains larger than $\sim 0.2 \mu\text{m}$ are too heavy and remain trapped in the gravitational field of the host galaxy. However these analysis have provided no statistical description of the grain size abundance. A common assumption is to consider a power law distribution, $N(a) \propto a^{-3.5}$, usually referred as the MRN model (Mathis, Rumpl & Nordsiek 1977). This describes the size distribution of dust grains in the Milk Way, but there is no guarantee that this model remains valid for IGM dust as well. On the other hand Bianchi & Ferrara (2005) have studied through numerical simulation the size distribution of grains ejected into the IGM. Assuming an initial flat size abundance they find that the post-processed distribution remains nearly flat and due to erosion sputtering the size range is slightly shifted towards smaller radii, $0.02 - 0.15 \mu\text{m}$. We refer to this as the BF model and evaluate the gray dust extinction for both MRN and BF cases. We also consider a uniformly sized dust model corresponding to a distribution $N(a) = \delta(a)$, with $a = 0.1 \mu\text{m}$ and for more descriptive purpose we also consider the less realistic value $a = 1.0 \mu\text{m}$.

The exact intergalactic dust composition is also not known, we focus silicate and graphite particles with material density $\varrho = 2 \text{ g cm}^{-3}$, and optical properties specified as in Draine & Lee (1984). Using these specifications we compute the extinction efficiency factor $Q_m^\lambda(a, z)$ by solving numerically the Mie equations for spherical grains (Barber & Hill 1990).

We set the mean interstellar yield to $y_Z = 0.024$ (Madau et al. 1996) corresponding to the value inferred from the Salpeter IMF (Salpeter 1955).

The star formation rate at different redshifts is known from a large body of measurements. The trend at redshifts $z \leq 1$ is well established with

$$\frac{\dot{\rho}_{\text{SFR}}(z)}{M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}} = 0.0158 (1+z)^{3.10}, \quad (5)$$

being the best fit to existing data (Hopkins 2004). On the other hand there is less agreement on the exact behavior at higher redshifts, with recent observations favoring a flat redshift dependence (Giavalisco et al. 2004). We follow the analysis of Inoue & Kamaya (2004) and consider two possible star-formation rates at $z > 1$:

$$\frac{\dot{\rho}_{\text{SFR}}(z)}{M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}} = \begin{cases} 0.136 & \text{(high SFH)} \\ 0.384 (1+z)^{-1.5} & \text{(low SFH)} \end{cases} \quad (6)$$

in units of solar mass M_\odot per year per Mpc volume.

Consistently with constraints derived in (Inoue & Kamaya 2004) we set $\chi = 0.01$. Since Eq. (4) is linear in this parameter the results can be simply rescaled for different values. For this particular choice the total dust density up to $z = 4.3$ is $\Omega_{\text{dust}}^{\text{IGM}} \sim 10^{-6}$, which is consistent with the direct constraints found in Paerels et al. (2002). In addition dust grains in the IGM can absorb the UV light in the Universe and re-emit in the far infrared contributing the FIRB. From the analysis of Aguirre & Haiman (2000) we find that for $\chi = 0.01$ cosmic gray dust would produce a background signal at $850 \mu\text{m}$ roughly 10% of the FIRB and only 1% at $200 \mu\text{m}$, thus well within the DIRBE/FIRAS limits.

In figure 1 we plot the B-band extinction (upper panels) and reddening (lower panels) as function of the redshift for BF (left panels) and MRN (right panels) grain size distributions. The solid and dash lines correspond to silicate and graphite grains respectively. Thick (thin) lines correspond to high (low) SFH models. Low SFH gives smaller extinction than the high case, consistently with the fact that low SFH produce a smaller amount of dust. The extinction is larger for graphite grains than silicate. Notice also that the extinction for the BF distribution is smaller than for the MRN case. This is because in the B-band the efficiency factor is constant, thus Eq. (4) scales as $N(a)/a$. Since smaller grains are more abundant in the MRN model than in the BF case, the corresponding extinction is larger.

As it can be seen from the plots of the color excess $|E(B-V)|$ these models cause very little reddening. Photometric measurements more accurate than 1% would be needed to detect the imprint of gray dust at high redshift.

In figure 2 we plot the case of uniformly sized grains with radii $a = 0.1 \mu\text{m}$ and $a = 1.0 \mu\text{m}$. As expected $a = 0.1 \mu\text{m}$ grains cause an extinction nearly a factor 10 larger than $1.0 \mu\text{m}$ particles, consistently with the $1/a$ dependence of A_B . Although these models are unrealistic from a purely astrophysical stand point, we can see that for $a = 0.1 \mu\text{m}$ the expected extinction and reddening are in agreement with those estimated assuming more realistic grain size distributions. Therefore without loss of generality we can use the uniform size approximation to study the effect of dust extinction on the dark energy parameter inference without the need to specify the exact form of $N(a)$. We can simply focusing on the typical size of gray particles and the other parameters specifying the IGM dust model.

3 DARK ENERGY INFERENCE

Supernova Type Ia observations measure the luminosity distance through the standard-candle relation,

$$m_B(z) = \mathcal{M}_B + 5 \log H_0 d_L(z), \quad (7)$$

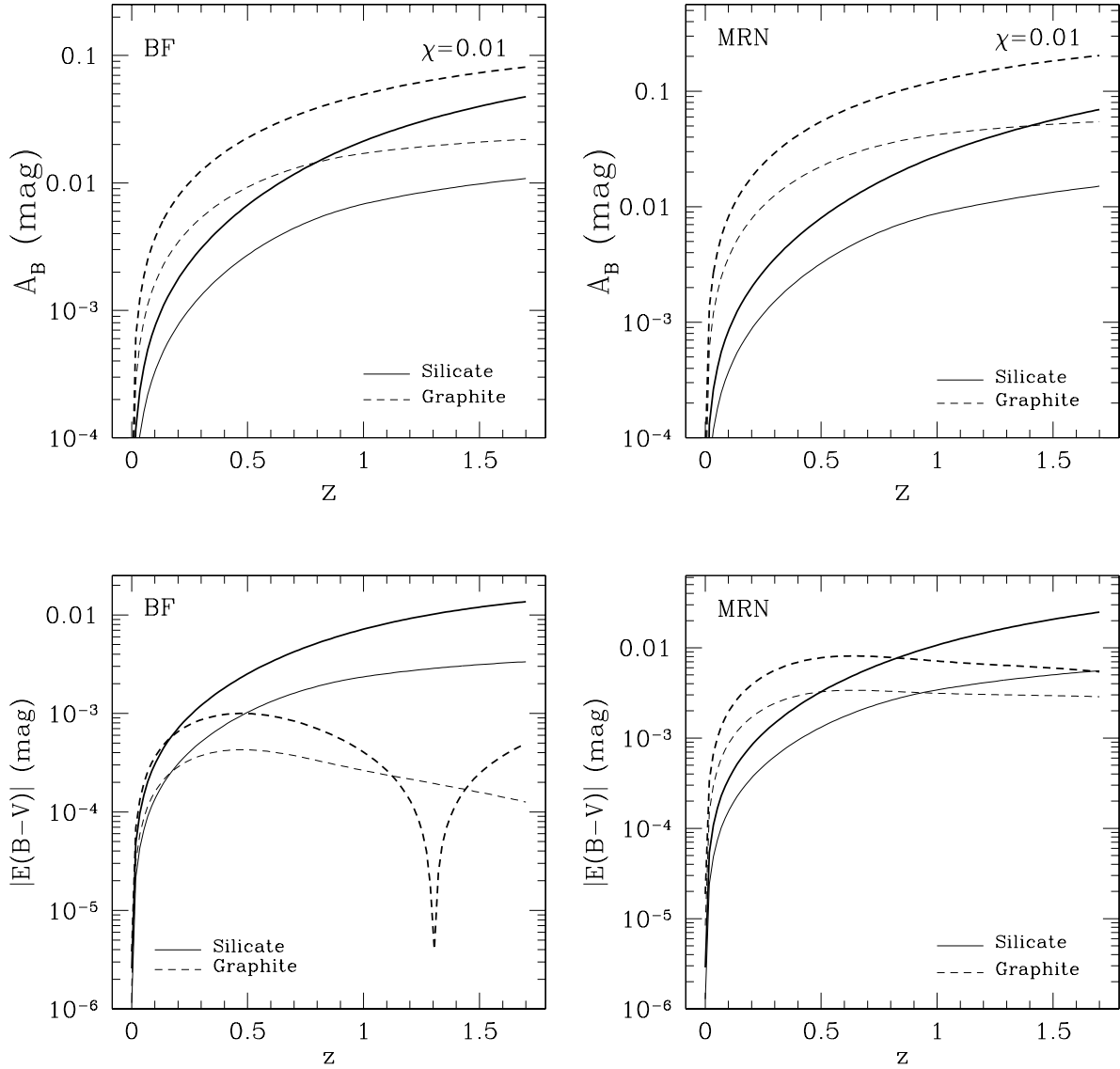


Figure 1. Cosmic gray dust extinction in the B-band (upper panels) and color excess (lower panels) as function of redshift of the source for BF (left panel) and MRN (right panel) grain size distributions in the range $0.02 - 0.15 \mu\text{m}$. Solid and dash lines correspond to silicate and graphite grains respectively. Thick (thin) lines correspond to high (low) SFH models.

where $m_B(z)$ is the apparent SN magnitude in the B-band, $\mathcal{M}_B \equiv M_B - 5 \log H_0 + 25$ is the “Hubble-constant-free” absolute magnitude and $d_L(z)$ is the luminosity distance.

Extinction modifies the standard-candle relation such that the observed SN magnitude is

$$\tilde{m}_B(z) = m_B(z) + A_B(z), \quad (8)$$

with $A_B(z)$ given by Eq. (4) evaluated at the B-band center rest-frame wavelength, $\lambda = 0.44 \mu\text{m}$. Hence supernovae are systematically dimmer than in a dust-free universe, and overestimate luminosity distances. Note that the extinction term in Eq. (8) corresponds to a redshift dependent magnitude offset. Previous studies of supernova systematics have limited their analysis to a simple magnitude offset that linearly increases with redshift (Weller & Albrecht 2002; Kim et al. 2004). On the contrary here we ap-

proach this type of systematic from a physically motivated standpoint. Having modeled the gray dust extinction as in Eq. (4), we can determine how astrophysical uncertainties in the cosmic dust model parameters affect dark energy parameter inference.

3.1 Monte Carlo Simulations

Using Eq. (8) we proceed by Monte Carlo simulating a sample of SN Ia data in the B-band in a given cosmological background for dust models listed in table 1. Then for each of these samples we recover the background cosmology by inferring the best fit dark energy parameter values and uncertainties in a dust-free universe through standard likelihood analysis.

We consider a constant dark energy equation of state w and a

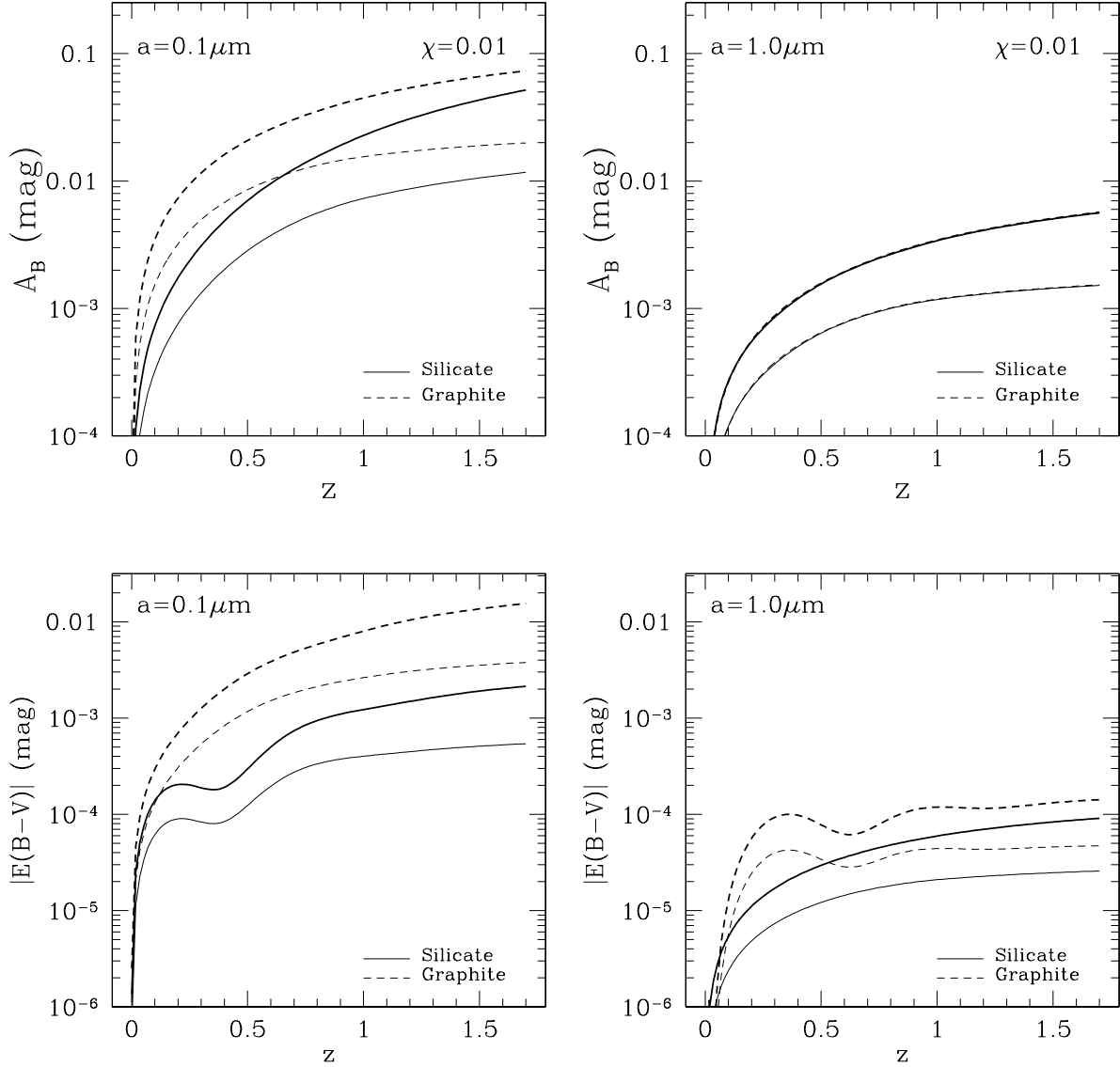


Figure 2. As in Fig. 1 for a uniform sized grains with $a = 0.1 \mu\text{m}$ (left panel) and $a = 1.0 \mu\text{m}$ (right panel).

Table 1. Grey dust models. For $a = 1.0 \mu\text{m}$ we only consider Silicate dust since Graphite causes the same extinction.

	χ	a	Type	SFH
A	0.01	0.1	Graphite	low/high
B	0.01	0.1	Silicate	low/high
C	0.01	1.0	Silicate	low/high

time-varying equation of state of the form (Chevallier & Polarski 2001; Linder 2003)

$$w(z) = w_0 + w_1 \frac{z}{1+z}. \quad (9)$$

For simplicity we focus on a SN experiment such as SNAP which goes very far in redshift. We assume the survey characteristics as specified in (Kim et al. 2004). We consider a flat universe with $\Omega_m = 0.3$ and assume a Gaussian matter density prior $\sigma_{\Omega_m} = 0.01$.

First we consider the case of a fiducial LCDM cosmology. In figure 3 we plot the marginalized 1 and 2σ contours in the $\Omega_m - w$ plane inferred from the data samples generated in models A (red dash), B (red dot) and C (black solid) for low (left panel) and high SFH (right panel). It can be seen that the overall effect of extinction is to shift the confidence regions towards more negative value of the dark energy equation of state. This is because the extinction dims supernovae increasingly with the redshift. Thus inferred distances are bigger than in a dust-free universe mimicking a more rapid accelerating expansion. For fixed values of Ω_m this requires the dark energy equation of state to be < -1 . As a result an unaccounted extinction moves the best fit dark energy model many sigma away from the true one. The effect is more dramatic in model A since $A_B(z) \gtrsim 0.01$ at $z > 0.5$, while it is negligible in model C since the extinction is a factor ten smaller. From figure 3 it is evident that the existence of gray dust particles with size $\sim 0.1 \mu\text{m}$ and a dust-to-total metal mass ratio of 0.01 in LCDM cosmology would cause

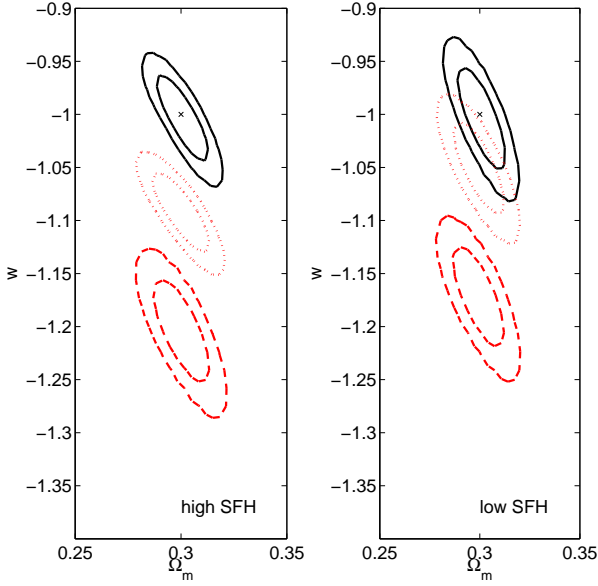


Figure 3. Marginalized 1 and 2σ confidence contours in the plane $\Omega_m - w$ inferred from data generated in models A (red dash), B (red dot) and C (black solid) in LCDM background. The left and right panels correspond to high and low SFH models respectively. The cross point indicates the parameter values of the fiducial cosmology.

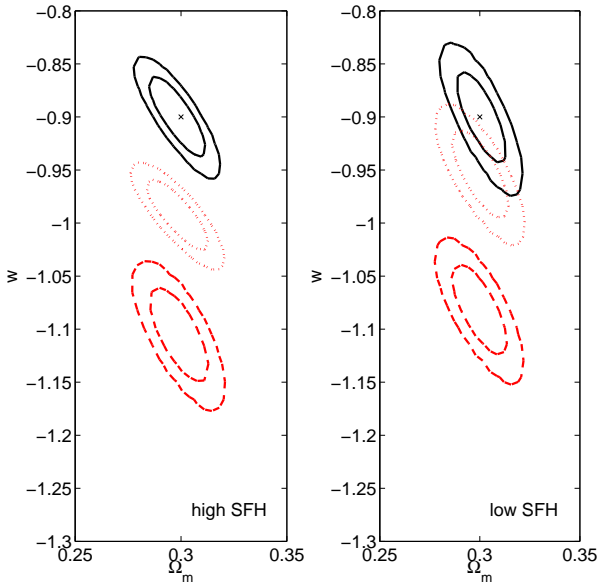


Figure 4. As in figure 3 with $w = -0.9$ dark energy fiducial cosmology.

an extinction that effectively mimic a phantom dark energy model, hence misleading us on the true nature of dark energy.

In the same manner IGM dust may prevent us from detecting a quintessence-like dark energy. For instance in figure 4 we plot the confidence contours in the case of a fiducial dark energy cosmology with $w = -0.9$. Again the effect of dust extinction is to shift the confidence regions towards more negative values of w . The amplitude of this effect is similar to the previous LCDM case and therefore is fiducial cosmology independent.

To be quantitative the extinction in model A causes a 20% bias

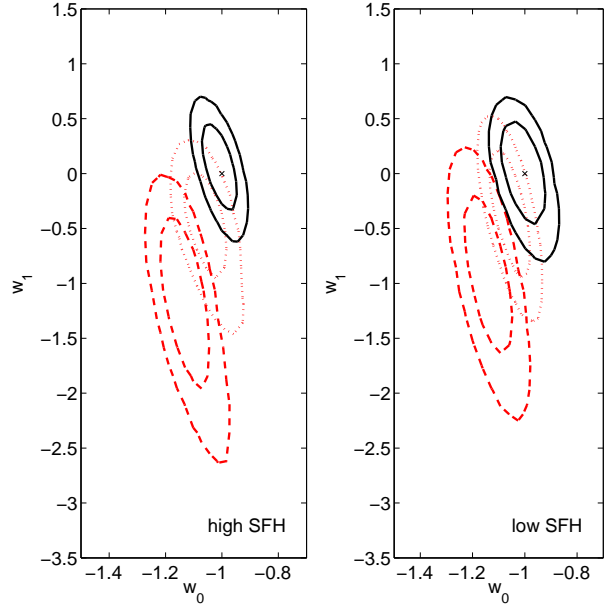


Figure 5. Marginalized 1 and 2σ contours in the plane $w_0 - w_1$ for dust models as in figure 3.

on the inferred values of w and 10% in model B. On the contrary model C does not affect the parameter inference.

A similar trend occurs for the constraints on the redshift parametrization Eq. (9). We plot in figure 5 the marginalized 1 and 2σ contours in the $w_0 - w_1$ plane for a fiducial LCDM cosmology. Notice that the size of the ellipses is altered, besides the amplitude of the shift is smaller than for the constant equation of state parameter. In fact while in model A the fiducial cosmology still lies many sigma away from the 95% confidence region, it is within the 2σ contours for model B. This is because the effect of the extinction is spread over two degenerate equation of state parameters. Indeed IGM dust parameters should be included in the cosmological fit along the line suggested by Kim & Miquel (2006).

3.2 SN-Gold Data Analysis

Can dust extinction affect the dark energy parameters inference from current SN Ia data? Despite the recent progress in the search for SN Ia, the magnitude dispersion is still large (~ 0.1 mag). Therefore the extinction effect is well within the experimental errors. As an example we consider the Gold sample (Riess et al. 2004) which extends up to $z_{max} \sim 1.7$ and therefore is more likely to be sensitive to gray dust extinction than the SNLS dataset (Astier et al. 2006) for which $z_{max} \sim 1$. In addition the estimated SN extinctions in the Gold dataset appear to be correlated with the magnitude dispersion (Jain & Ralston 2006). We assume a flat universe with prior $\Omega_m = 0.27 \pm 0.04$. Using Eq. (8) we fit the Gold data accounting for the extinction of dust model A. We find $w = -0.90 \pm_{0.21}^{0.17}$ at 1σ . On the contrary the fit without extinction gives $w = -0.96 \pm_{0.16}^{0.18}$. Thus the shift is less than 1σ . The fact that the best fit value is slightly > -1 should not be surprising. Comparison with the SNLS data shows that SNe in the Gold sample are slightly brighter. Nevertheless the LCDM is within 1σ uncertainty. Notice that the direction of the shift is consistent with the result of the Monte Carlo analysis. In fact accounting for the extinction term

allows models with a larger value of w to be consistent with the data.

4 NEAR-IR COLOR ANALYSIS AND DECREMENT OF BALMER LINES

As we have seen in Section 2.2 it is very difficult to detect the signature of gray dust through reddening analysis in the optical wavelengths. It has been suggested that broadband photometry in the near-IR could be more effective. For instance Goobar et al. (2002) estimate in 1% the spectro-photometric accuracy necessary to detect the dust reddening in the I, J and R bands. In figure 6 we plot the color excess $|E(V-J)|$, $|E(R-J)|$ and $|E(I-J)|$ for our test-bed of cosmic dust models. For low SFH models the color excess is too small to be detectable with 1% photometry. Only model A in the high SFH case would be marginally distinguishable. In general we find that our estimates are a factor two smaller than in Goobar et al. (2002). Given the difficulty of performing such accurate near-IR measurements, distinguishing the effect of cosmic dust will be a challenging task.

A possible alternative is to consider the decrement in the relative strength of the Balmer lines in the host galaxy spectrum. The recombination of ionized hydrogen atoms causes the well known H_α and H_β emission lines at 6563 Å and 4861 Å respectively with intensity ratio $r_{H_\alpha/H_\beta} = 2.86$. Deviations from this value are indicative of selective absorption. For instance in the case of an extinction law with negative slope, the blue light is dimmed more than the red one, hence causing $r_{H_\alpha/H_\beta} > 2.86$. In figure 7 we plot the absolute value of the relative decrement of the Balmer lines as function of redshift for models A, B and C respectively. We may notice that the amplitude of the decrement for model A and B is within standard accuracy of high signal-to-noise spectroscopy. It is also worth noticing that for $1.0 \mu\text{m}$ Silicate grains (model C) the extinction law at $z > 0.4$ changes slope causing $r_{H_\alpha/H_\beta} < 2.86$. Deep redshift spectroscopic surveys can in principle be used to track the trend of the Balmer line decrement and provide a complementary method to test the cosmic dust extinction. However IR observations are necessary in order to measure the H_α emission of high redshift sources. As an example the SDSS catalog of galaxy and quasar spectra spans the range $3800 < \lambda < 9200 \text{ Å}$ therefore the H_α cannot be detected for objects at $z \gtrsim 0.25$. The next generation of satellite surveyors will be equipped for IR-spectroscopy and capable to provide such measurements.

5 TESTING DISTANCE-DUALITY RELATION

A well known result of metric theories of gravity is the uniqueness of cosmological distances (Etherington 1933). Thus measurements of the luminosity distance $d_L(z)$ and angular diameter distance $d_A(z)$ at redshift z are linked through the duality relation (Linder 1988; Schneider et al. 1992)

$$Y \equiv \frac{d_L(z)}{d_A(z)(1+z)^2} = 1. \quad (10)$$

As discussed in (Bassett & Kunz 2004b) testing this equality with high accuracy can be a powerful probe of exotic physics. Violations of the duality relation are predicted by non-metric theories of gravity, varying fundamental constants and axion-photon mixing (Bassett & Kunz 2004a; Uzan et al. 2004) just to mention a few. Also astrophysical mechanisms such as gravitational lensing and dust extinction can cause deviation from Eq. (10).

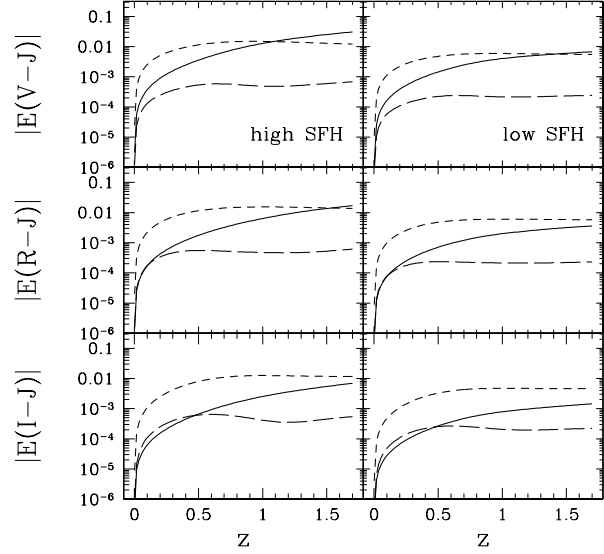


Figure 6. Absolute value of color excess $E(V-J)$, $E(R-J)$ and $E(I-J)$ versus redshift for models A (short-dash), B (solid) and C (long-dash) in the case of high (left panel) and low SFH (right panel).

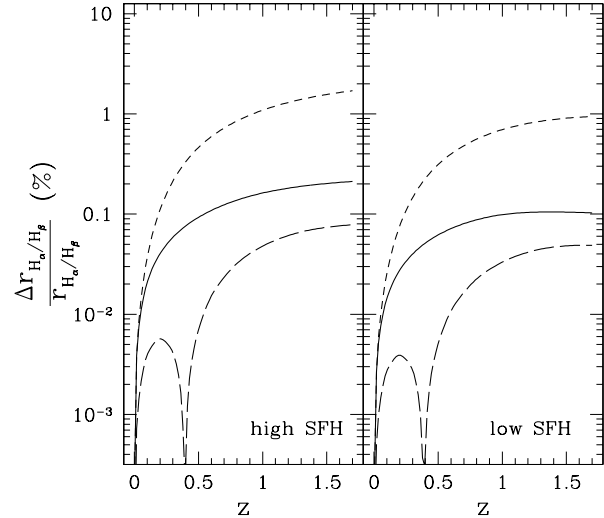


Figure 7. Relative decrement of Balmer lines for dust models as in figure 6.

From Eq. (7) and Eq. (8) it is easy to show that in the presence of dust extinction the deviation from Eq. (10) is given by

$$\Delta Y(z) = 10^{\frac{1}{5} A_B(z)} - 1. \quad (11)$$

Therefore if SN Ia are dimmed by intergalactic dust absorption, this would be manifest in the violation of the duality relation.

The distance-duality relation can be tested using SN Ia data and angular diameter distance measurements from detection of baryon acoustic oscillations (BAO) in the galaxy power spectrum (Bassett & Kunz 2004b; Linder 2005). Over the next decade several surveys of the large scale structures will measure $d_A(z)$ with few percent accuracy over a wide range of redshifts. Similarly fu-

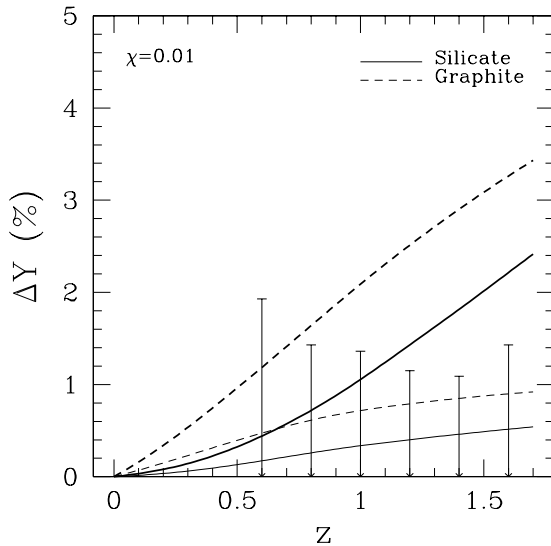


Figure 8. Percentage deviation from the distance-duality relation as function of redshift. The dash and solid lines represent the violation caused by dust extinction for $0.1 \mu\text{m}$ Graphite and Silicate grains respectively. Thick (thin) lines correspond to high (low) SFH. The errorbars are the errors on the duality test as expected from upcoming SN Ia and BAO surveys. At $z < 0.5$ the errors on angular diameter distance measurements are not enough accurate for testing the duality.

ture SN Ia surveys such as SNAP are designed to control intrinsic supernova systematics within few percent which would provide luminosity distances measurements with 1 – 2% accuracy.

We forecast the sensitivity of future distance-duality test by error propagation of Eq. (10). We assume the expected errors on the angular diameter distance for a galaxy survey of $10,000 \text{ deg}^2$ with spectroscopic redshifts as quoted in (Glazebrook & Blake 2005).

In figure 8 we plot Eq. (11) for dust models A and B in the case of high (thick lines) and low SFH (thin lines). The errorbars correspond to the expected uncertainty of the distance-duality test. It can be seen that for high SFH, Silicate and Graphite particles of size $0.1 \mu\text{m}$ would caused a clearly detectable violation of the distance-duality relation.

6 CONCLUSION

The goal of the next generation of SN Ia experiments is to determine the dark energy parameters with high accuracy. For this to be possible systematic effects must be carefully taken into account. Here we have studied the impact of intergalactic gray dust extinction. We have used an astrophysical motivated modeling of the IGM dust in terms of the star formation history of the Universe and the physical properties of the dust grains. We have identified a number of models which satisfy current astrophysical constraints such those inferred from X-ray quasar halo scattering and the amplitude of the FIRB emission. Although characterized by negligible reddening IGM dust may cause large extinction effects and strongly affect the dark energy parameter estimation. In particular for high star-formation history we find that dust particles with size $\sim 0.1 \mu\text{m}$ and a total dust density $\Omega_{\text{dust}}^{\text{IGM}} \sim 10^{-6}$ may bias the inferred values of a constant dark energy equation of state up 20%.

Current SN Ia data are insensitive to such effects since the amplitude of the induced extinction is well within the supernova magnitude dispersion. Near-IR color analysis would require an accuracy better than 1% to detect the signature of these IGM dust particles. On the other hand IGM dust arising from high SFH can be distinguished from the decrement of Balmer lines with high signal-to-noise spectroscopy. We have also shown that cosmic dust violates the distance-duality relation, and depending on the dust model this may be detected with future SN Ia and baryon acoustic oscillation data.

It is worth remarking that a number of caveats concerning the physics of the IGM have been assumed throughout this analysis. Specifically we have considered a redshift independent dust-to-total-metal mass ratio. Unfortunately we still lack of a satisfactory understanding of the intergalactic medium both theoretically and observationally which would allow us to make more robust prediction about IGM dust extinction. Indeed if we happen to live in a Universe with a total gray dust density $\Omega_{\text{dust}}^{\text{IGM}} \sim 10^{-6}$ extinction effects on SN Ia observations must be considered more than previously thought. The risk is to miss the discovery of the real nature of dark energy.

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